Electron Beam-Produced Plasmas

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***Abstract*—High-energy electron beams offer a unique alternative to discharges as plasma sources for material processing. In this paper, we present several images of sheetlike beams produced in a variety of gases and in different configurations. In addition to their aesthetic value, the images provide insight into the plasma and system properties.**

***Index Terms*—Electron beams, emission, plasma generation, plasma materials-processing applications, plasmas.**

THE U.S. Naval Research Laboratory has developed a material processing system that utilizes a multikilovolt electron beam to produce the plasma. Beam-produced plasmas differ from conventional discharges [1] and offer unique capabilities in processing. These include a low electron temperature, which provides a low plasma potential and, thus, limits the energy at which ions will impact substrates. This low ion energy may be useful in the processing of soft materials [2]. The low electron temperature will also lead to the formation of dense continuous-wave ion–ion plasmas in attaching gases [3], [4] and may be useful in reducing the damage associated with electron-induced charging in etching applications. The relative density of species, which is unique to high-energy electrons, can also lead to beneficial effects in deposition [5] and nitriding [6] applications.

In its typical embodiment, the system uses a sheetlike electron beam that is magnetically confined so as to minimize collisional spreading, resulting in a well-defined source volume. The on-axis plasma densities are on the order of $10^{10} - 10^{11}$ cm^{-3}, and electron temperatures are between 0.3 and 1 eV, depending on the ambient gas. Outside of the beam volume, the densities and temperatures are less. Thus, depending on the operating conditions and the location of adjacent surfaces, ions will arrive with energies up to about 5 eV [1].

The images shown in this paper are side views of the electron beam-generated plasma, with the beam propagating horizontally and the magnetic field aligned coaxial with the direction of beam propagation. The plasmas are viewed through 6-in diameter ports. Each beam in the images is approximately 2 keV, the beam current density is typically 1–5 mA/cm, and the magnetic field is about 150 Gauss. In Fig. 1(a) and (b), beam-generated plasmas were produced in 50 mtorr of neon and nitrogen, respectively. In noble gases like neon, diffusion to the chamber walls determines the ion and electron loss rates, whereas in molecular gases like nitrogen, the dominant loss mechanism is electron–ion recombination $(e^- + \mathrm{N}_2^+ \rightarrow 2\mathrm{N})$. Recombination is a comparatively fast process, particularly when electron temperatures are low. Thus, the plasma density is larger, its breadth is greater in noble gases compared with those in molecular gases, and from the images, the region of light emission also tends to be broader in neon than in nitrogen.

The image shown in Fig. 1(c) is a plasma produced in a mixture of argon and nitrogen, and a stage is seen in close proximity to the beam. This configuration is typical for processing. Note here that beam propagation is largely unaffected by the presence of the stage. Although the mixture contains both argon and nitrogen in equal quantities, the molecular gas most strongly influences the bulk plasma properties in terms of both spatial decay and electron temperature. This behavior is observed because, in addition to the diffusion to the walls, charge exchange between the noble gas ions and the molecular gas proceeds rapidly as an additional loss mechanism of noble gas ions $(\mathrm{Ar}^+ + \mathrm{N}_2 \rightarrow \mathrm{Ar} + \mathrm{N}_2^+)$.

The image shown in Fig. 1(d) is a two-beam system [7] that is compatible with roll-to-roll processing platforms. In processing experiments, the treated material was suspended between the two beams. This configuration was specifically developed to treat porous media but could be used to treat both sides of flexible substrates. In this image, the background gas was a mixture of argon and oxygen, and here again, the molecular gas strongly influences the plasma properties.

In conclusion, the images show electron beam-generated plasmas produced in a variety of gases and in different embodiments. While the images were chosen largely for their aesthetic appeal, they do provide insight into gas-phase behavior of the plasma.

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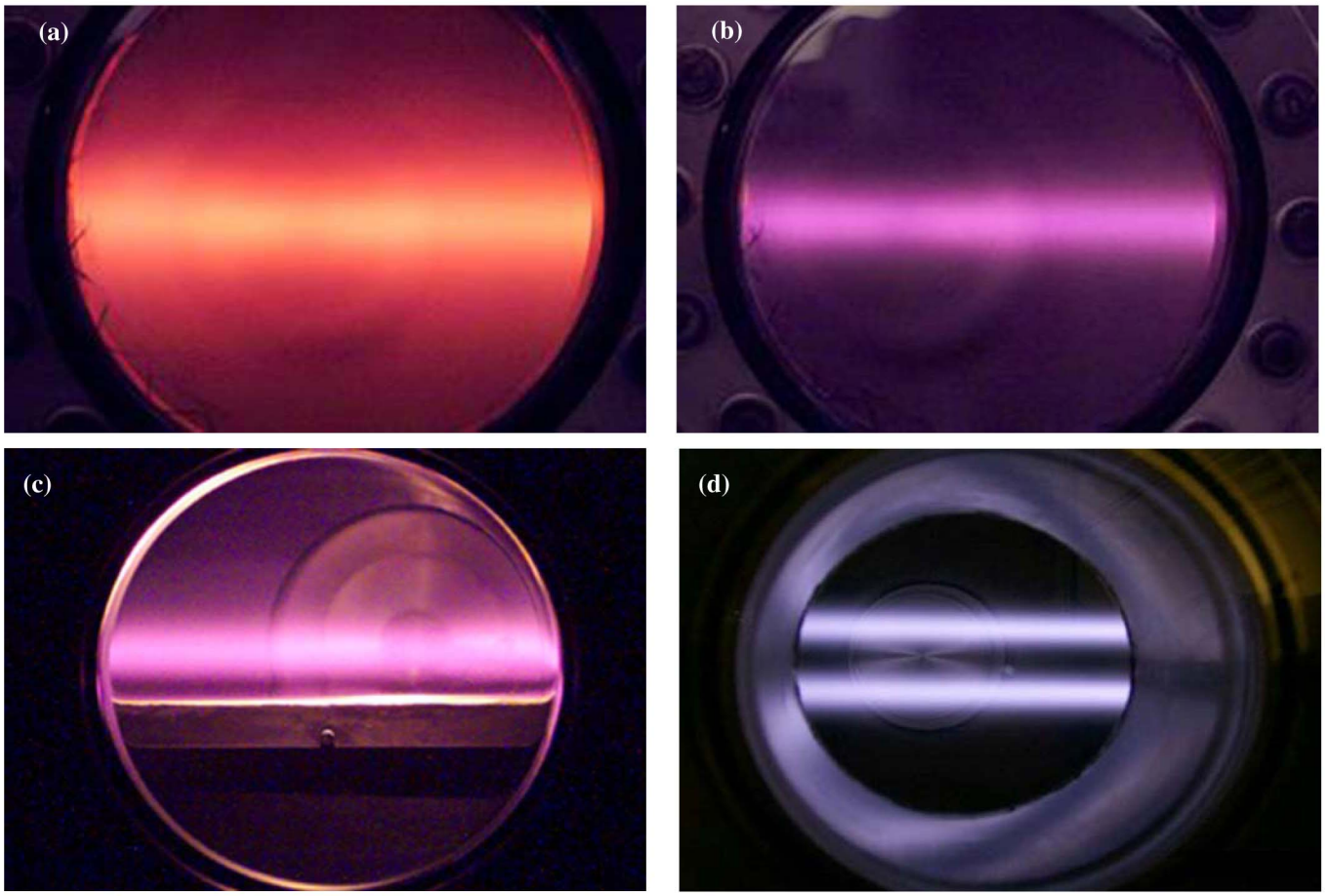

Fig. 1. Side views of magnetically confined, sheetlike, electron beam-generated plasmas produced in (a) neon, (b) nitrogen, (c) an argon/nitrogen mixture, and (d) a two-beam system produced in an argon/oxygen mixture. The latter two are images of plasma processing configurations. In all images, the electron beam propagates horizontally, and the magnetic field is codirectional with the beam.